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Comparison of fuel consumption and emission characteristics of various marine heavy fuel additives

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HIGHLIGHTS

- This study investigated the effects of marine fuel additives on performance results.
- Chemical laboratory tests and engine test bed analyses were conducted.
- Improved fuel stability was detected with certain dosages of fuel additives.
- Some additives reduced fuel consumption, but other increased it.
- The presence of additives altered the emission characteristics of the fuel.

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ABSTRACT

Major shipping companies utilize fuel oil additives to reduce fuel costs and to comply with emission regulations. Although the use of fuel additives for marine heavy fuel oil has increased dramatically, their effects on performance have not been verified. This study investigated the effects of fuel additives, not only at the scale of the engine test bed but also through chemical laboratory tests. Fuel separability tests were conducted to evaluate fuel oil stability. The results indicated that there was improved stability with certain dosages of fuel additives. Fuel combustion and ignition characteristics were evaluated via a Fuel Combustion Analysis (FCA) test, which showed that combustion parameters, including the pressure trace and rate of heat release (ROHR), were significantly affected by the use of fuel additives. The ROHR results showed modified performance indicators, particularly in regard to the position of the ROHR, ignition delay, end of main combustion, and end of combustion. The testing only aimed to determine the tendency at low engine loads, because engines typically operate at low loads within emission controlled areas. The engine test results showed that some additives were associated with reduced fuel consumption, but that some resulted in higher specific fuel oil consumption levels than those for fuel oils without additives. Nitrogen oxide (NOx) and particulate matter (PM) emission characteristics were also investigated, and data revealed that fuel additives affected the emission components.

1. Introduction

Global economic risks and depressed shipping environments in recent times have forced shipping companies to focus on cost savings. According to many reports concerning shipping costs, fuel use accounts for 30–55% of the total vessel managing capital depending on the type of ship [1].

Because of the high fuel-consuming characteristics of ships, fuel related problems are common occurrences, and these can take place while bunkering (i.e. storing), supplying, and consuming fuels. In particular, filter blockages, fuel starvation, phase separation, and sludge creation are some of the problems that can be caused by poor fuel quality [2].

Shipping companies are interested in minimizing fuel consumption along with ensuring safe engine operations. In conjunction with fuel economies, environmental marine regulations also influence the shipping and ship construction industries. Fuel additives have been recommended to minimize fuel consumption and to reduce emissions. However, the performances of most fuel additives supplied to the shipping sector have not been verified. Therefore, questions remain in regard to the performance benefits associated with the increased use of fuel additives.

The mechanism of particulate matter (PM) reduction by fuel additives [3], and the characteristics of additive-mixed fuels such

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Nomenclature

SFOC	specific fuel oil consumption
NOx	nitrogen oxide
PM	particulate matter
FCA	fuel combustion analysis
BET	Brunauer Emmett Teller
ROHR	rate of heat release
HFO	heavy fuel oil
DO	diesel oil
FTIR	Fourier transformed infrared
CO	carbon monoxide
CO_2	carbon dioxide
P.ROHR	position of ROHR (rate of heat release)
AR	accumulated ROHR (rate of heat release)
M.ROHR	maximum ROHR (rate of heat release)
ASTM	American Society of Testing Material
IP	Institute of Petroleum
CCAI	calculated carbon aromaticity index
ECN	estimated cetane number
MCD	main combustion delay
ρ_{15}	fuel density at 15 °C
ν	fuel viscosity (cSt)

as the atomization, evaporation, mixing, ignition, and combustion properties [4] have been studied. Kar et al. [5] simulated soot creation in large two-stroke marine diesel engines. The simulation used a multi-step soot model derived from laser extinction measurements in an optically accessible constant volume combustion chamber. This model can be applied to identify SOx and sulfuric acid distributions. Guerry et al. [6] studied injection-timing effects on a diesel methane dual-fuel combustion engine. Such technology represents a potential design strategy for future engines because of its promising capacity to lower engine emissions of nitrogen oxides (NOx) and PM. The study varied the start of the injection timing, and the results confirmed that there was an increased fuel conversion efficiency. The effects of fuel additives on engine emissions and efficiency have been investigated in on-road engines [7]. Teresa et al. [8] summarized recent research on catalytic oxidation and jet fuel reformation. Fe, Co, and Mo are known to create more extensive molecular surface area. A Brunauer Emmett Teller (BET) analysis confirmed that Fe had the highest reactivity; it is widely used in fuel additives as a combustion catalyst. Han et al. [9] investigated the changes in fuel properties when fuel additives were used on board marine vessels. Bennet [10] reported that the addition of manganese-containing fuel additives could not only save fuel oil by reducing excess air but also reduce the amount of SO_3 generated by boilers using heavy fuel oil (HFO). Babushok et al. [11] studied the effect of additives on the formation of polycyclic aromatic hydrocarbons. They found that metallic additives suppressed soot formation; they also reported on the suppression mechanism. Gürü et al. [12] studied changes in fuel properties due to the use of additives and found that Mn lowers the fuel freezing point to a greater degree than Cu, Mg, or Ca. Tracy et al. [13] reported that hydrogenated monoterpenes decrease the cloud point of diesel. Additionally, hydrogenated forms of myrcene and limonene can be used as blending agents in diesel. Fennell et al. [14] studied the reaction between NO and Fe at 500–900 °C in terms of reaction rates and possible mechanisms. Rebola and Costa [15] studied emission reductions from heavy fuel oil-fired furnaces and concluded that simultaneous reductions of NO_x and PM are extremely difficult to achieve. Mwangi et al. [16] summarized the technical achievements made in regard to increased engine efficiencies and emission reductions in diesel engines. They suggested that the use of green fuels is effective for increasing engine efficiency and reducing emissions. Bonatesta et al. [17] studied potential fuel savings in modern four-stroke gasoline engine designs with a focus on implementing feasible strategies for variable camshaft timing. Specifically, they found that the engine compression ratio and fuel injection technology can have key benefits for fuel economy, and that variable camshaft timing can be helpful for achieving additional improvements in the fuel economy. Vinicius et al. [18] studied ethanol-based dual-fuel combustion under low-load conditions. That study found that increased efficiency could be achieved by adjusting exhaust gas recirculation, intake air pressures, and rail pressures. Following performance optimization, NOx and soot emissions were reduced to 65% and 29%, respectively. Zhi-Hui et al. [19] studied PM emission characteristics and engine performance when blended fuel oil was used, and the fuel oil consisted of biodiesel and butanol or pentanol. That study found that blended fuel oil could increase the brake thermal efficiency and brake specific fuel consumption. The blended fuel oil did also reduce elemental carbon and diesel particulate matter, but water-soluble organic carbon and the organic carbon fraction increased. Wang et al. [20] studied dieseline, which is a blend of diesel and gasoline, to determine if improvements in the combustion efficiency and emission reductions could be achieved by reducing the ignition delay. Li et al. [21] also simulated dieseline effects and concluded that while pure diesel could be effective at low loads, dieseline would be efficient at increased engine loads. Matteo et al. [22] studied injection and Miller cycle effects in a large-bore marine engine (IMO Tier 2 compliant marine engines generally employ the Miller cycle). Specifically, that study investigated the split injection effect in conjunction with Miller timing and concluded that split injection reduced ignition delay. While increased ignition delay did increase the fuel economy, it had no advantages in regard to emission reductions. Most studies of fuel additives have examined on-road vehicles that consume distilled paraffinic fuel oil. Additive performance is typically verified in a combustion chamber and/or boiler, and it was hard to find relevant engine studies to compare to our work. Most previous studies focused on in-engine effects such as the Miller timing, injection optimization, cam timing optimization, and emission calculations via computational fluid dynamics (CFD); we found comparatively few studies of residual fuels and their associated additives.

This study evaluated the performance of a wide selection of marine fuel oil additives including both internationally known and newly developed products. Borkowski et al. [23] suggested that there is a correlation between ship speed and engine performance on board a vessel. However, test conditions on board a vessel are not stable, and thus, the results are not reliable for test cell analysis. Therefore, the present study utilized a test bench to eliminate external factors such as wind, currents, and waves, which can decrease the reliability of test results by influencing the engine output. The testing was focused on low-load operations as this is the present trend in the shipping sector and stringent emission regulations are enforced for inshore areas where very low-load operations usually occur. Laboratory tests were also performed for each fuel additive at a certified test facility of the Korea Research Institute of Chemical Technology.

The results of this study should be applicable to the marine shipping and equipment sectors and provide valuable information about the feasibility of achieving fuel savings and emission reductions.